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ROOT SYSTEMS OF CERTAIN FORAGE CROPS IN RELATION TO THE MANAGEMENT OF AGRICULTURAL SOILS

By

THOMAS PAVLYCHENKO

Published under the authority of the Honourable J. A. MacKinnon, Chairman of the Committee of the Privy Council on Scientific and Industrial Research, and the Honourable J. G. Gardiner, Minister of Agriculture.

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ROOT SYSTEMS OF CERTAIN FORAGE CROPS IN RELATION TO THE MANAGEMENT OF AGRICULTURAL SOILS[1]

By THOMAS PAVLYCHENKO[2]

Introduction

The economic value of agricultural soils is based upon their productivity. The productiveness of land, however, is not a constant quality. Even within the same soil type and under relatively uniform climatic conditions, it varies widely in accordance with the system of land utilization and soil management. Defective management produces seriously eroded and weedy fields yielding poor crops even in districts with good soils. Under good management fields free from erosion and weeds often produce good crops on land of only fair quality. Differences in the productivity of land arising from improper management of soil are pronounced, not only in areas with ample rainfall, but especially in areas of low precipitation (2, 3, 4, 32).

Unfortunately, the fundamentals of soil management are often neither clearly understood nor applied in practical farming. Agricultural lands consequently become extremely weedy (6, 8, 9, 10). Weeds appropriate large amounts of soil moisture and cause considerable reduction in crop yields (1). These reductions often range from 18 to 45%, depending upon the species of weed, the degree of infestation, and the effectiveness of the control measures employed (33). Damage may be as little as 4% with light infestations and as much as 84% under heavy infestations (37) which preclude profitable farming even on good soils (13, 14, 21, 23, 27, 47, 50). Good soil management should achieve proper utilization of soil moisture throughout the growing season (11, 12), elimination of weeds, and preservation of natural soil structure as far as is consistent with necessary field operations (1, 17, 25).

Weed infestation and pulverization of soil are associated with long, continuous use of land for annual crops. The amount and nature of soil-binding materials left by annual crops are not sufficient to offset pulverization in tillage operations (64, 65). The practice of cutting annual crops after weeds have shattered their seed provides ideal conditions for increase of weed seeds in the soil. Unless some practical method is found to check accumulation of weed seeds and to supplement the quantity of root fibre produced by annual crops, the menace of weed infestation and erosion to arid agricultural lands will become increasingly grave.

The fact that the newly broken sod of some perennial grasses does not drift for several years, and only very gradually becomes reinfested with weeds,

[1] *Contribution from the Department of Botany, University of Nebraska, and the Research Laboratory of Plant Ecology, University of Saskatchewan, with financial assistance of the National Research Council of Canada, the Dominion Department of Agriculture, and the Carnegie Corporation of New York. The work was submitted to the University of Nebraska as a thesis for the degree of Doctor of Philosophy.*

[2] *Research Professor in Plant Ecology, University of Saskatchewan.*

indicates that the remedy may be found among the perennial forage crops. Such crops must be of high competitive efficiency and capable of producing large quantities of strong roots. Root fibre binds pulverized soil into larger structural aggregates, which in time become stabilized and present con siderable resistance to the action of wind and water (15, 18, 25). Detailed information concerning the underground parts of perennial grasses, annual grains, and weeds is, therefore, of primary importance for intelligent management of soil (55).

In order that experiments of the type reported here may if necessary be repeated for comparison under different ecological conditions the methods and statistical data are reported in some detail (26).

This work was pursued throughout a period of seven years (1933 to 1939). It includes examination of the roots of *Agropyron cristatum* (L.) Beauv., *Agropyron pauciflorum* (Schwein.) Hitchc., and *Bromus inermis* Leyss., and a quantitative determination of the soil-binding qualities of the roots of certain native and cultivated grasses and alfalfa. A study of the effect of root fibre of certain grasses upon soil structure was also made, and the use of perennial forage grasses in rotation with grain crops for control of common annual weeds was investigated. The three cultivated grasses were studied at the University of Saskatchewan in Canada, and the seven native prairie grasses, winter wheat and alfalfa, at the University of Nebraska in the United States.

Environment

The arid climate at Saskatoon, Saskatchewan, with hot summers and severe winters, supports vegetation of the mixed prairie type. At Lincoln, Nebraska, where most of the species herein described were studied, the climate is typically semi-arid with a much higher annual precipitation than that prevailing at Saskatoon, approximately the same temperatures in summer, but decidedly milder winters. Under these conditions the more diversified and luxuriant flora of the true prairie is developed.

The most important meteorological data concerning both ecological regions are included in Table 1.

TABLE 1

METEOROLOGICAL DATA FROM THE ECOLOGICAL REGIONS AROUND SASKATOON, SASKATCHEWAN, AND LINCOLN, NEBRASKA

	Saskatoon	Lincoln
Climate	Arid	Semi-arid
Vegetation	Mixed prairie	True prairie
Maximum summer temperature	104° F.	100° F.
Minimum winter temperature	−45° F.	−20° F.
Average maximum summer temperature	85.7° F.	85° F.
Length of growing season, days	145	165
No. days free from damaging frost	118	140
Depth of frost line, inches	73	24
Clear days in summer, %	70 to 80	60 to 72
Annual precipitation, inches	13.5	28
Percentage precipitation falling during growing period	50 to 80	76 to 79

The soil at Saskatoon is a chocolate silt loam, rich in humus and with a well-defined granular structure. The amount of humus decreases very gradually with increasing depth, until at 5 feet below the surface the soil consists of a virtually humus-free mixture of clay and fine sand.

The soils at Lincoln belong to the prairie or chernozem groups. The A horizons of these soils are generally fertile, dark in colour, and of a coarse granular structure. The B horizons are yellowish to brownish in colour and show columnar structure. In both regions the soils are high in fertility, relatively non-acid and unleached.

Precipitation, the chief limiting factor to plant growth at Saskatoon, is limiting only to a lesser degree at Lincoln.

Root Systems of *Agropyron cristatum*, *A. pauciflorum*, and *Bromus inermis*

Methods

This study included an investigation of the number of seminal and nodal roots per plant (7, 16, 38, 43, 44, 45, 46, 51, 52, 63) of three perennial forage grasses; a quantitative study of entire root systems of spaced plants excavated 5, 15, 30, 60, 90, 660, and 800 days after emergence; a determination of the amount and distribution of root material produced in sods, and an examination of the quantity and physical condition of dead root fibre in the soil, which was under regular cultivation for three years after the sods were broken.

All the plants studied were grown under field conditions. As many as 78 plants per species were excavated and analysed in early stages of growth, but only one or two representative specimens were examined during the second and third seasons of growth.

The entire root systems of these plants were exposed by the soil-block washing method (36). Roots were preserved in a 4% solution of formaldehyde, and later placed in a large, shallow tank for analysis. The number and extent of seminal and nodal roots were recorded separately. Length of all main roots and their branches in smaller plants was determined by actual measurement. Number and length of branches of more mature plants were computed from random sample counts and measurements. Beginning at the ground level, the root system was divided into horizontal strata, each 12.5 cm. deep, until the depth of greatest penetration was reached. The average frequency of branches of the first order per cm. of main root was determined separately at each depth, from 250 counts. Length of main roots multiplied by mean frequency of branches gave the number of branches at each depth. Average length of branches of the first order was determined on the basis of 250 measurements taken at each depth. By multiplying the number of branches by their respective mean lengths at each depth and summing up the products, the total length of all branches of the first order was obtained. The number and length of branches of the second and third orders were secured in a like manner, except that the number of branches of each order was computed from their respective mean frequencies and the length of branches of the order which immediately preceded them.

A number of plots, each one rod square, of crested wheat grass, slender wheat grass, and brome grass were seeded on May 20, at rates of 25, 30, and 35 pounds per acre, respectively, in 1933 and in 1935. The amount and nature

of root fibre deposited by these grasses when grown in sod was determined from samples excavated in these plots. When the plots seeded in 1933 were in their fourth season of growth and those of 1935 in their second season, blocks of sod 30.5 by 76 cm. in surface area and 15, 30.5, and 152 cm. deep, respectively, were excavated in triplicate and carefully washed. The extent and nature of the root systems and the dry weights of underground materials were determined. Seven-year-old plots of *Agropyron cristatum* and *Agropyron pauciflorum*, which had been established in 1927 and grown under similar conditions, were broken in 1934 and the land was sown to grain on May 1, 1937. Four random soil samples 30.5 cm. long by 30.5 cm. wide and 15 cm. deep and four others of the same length and breadth but 30.5 cm. deep were obtained from each sod on June 15 of the same year.

Dead root fibre was separated from the samples by the flotation method. Samples were soaked in water for 24 hours. They were then placed in boxes with sides and bottoms made of screen of 0.2 mm. mesh and submerged. Clay and silt were washed through the screen by gentle movement of the boxes. Dead fibre, as it rose to the surface, was collected with a large spoon made of similar screen. Larger granules and clods were transferred to similar boxes made of screen of 1 mm. mesh and the procedure repeated. This continued through increasingly larger screens until the last bits of root fibre were separated from the soil. The amount of vegetable matter in each sample was determined both in oven-dry weight and in combustible material.

Seminal Root System

Seminal roots have been erroneously called temporary roots (63). Results obtained in this and similar studies over a period of nine years gave conclusive evidence that, in annual grasses in arid climates, seminal roots function throughout the entire growing season, and what is more important, they are frequently the only roots supporting the plant from emergence to maturity (35)

The number of seminal roots per plant was generally small. It varied within narrow limits in each species, and apparently was governed by a definite genetic factor. In *Avena fatua* L., for instance, three was the constant number of seminal roots. In *Avena sativa* L., the average number in different years varied from 3.1 to 3.5; in *Triticum aestivum* L., from 3.6 to 5.0; in *Secale cereale* L., from 4.5 to 5.3; and in *Hordeum distichon* L., from 6.5 to 8.5 (38). Annual grasses with greater numbers of seminal roots were more capable of normal development under adverse conditions than were those with fewer such roots (35, 39).

The number of seminal roots per plant was smaller in the perennial grasses studied than in the annual grain crops previously named. There were averages of 1.6, 2.6, and 2.4 seminal roots in *Agropyron cristatum* at 5, 15, and 30 days. and still fewer in *A. pauciflorum* (1.5, 1.2, and 1.1 at the same ages). *Bromus inermis* gave averages of 2.3 in five days and 2 at each of the other stages (Table 2).

Of the seedlings of *Agropyron cristatum* excavated at the five-day stage, 55.5% had only one seminal root, 33.8% developed two, and 10.7% had three (Table 3). Plants with one and two roots were normal, but those with three roots were very weak. At 15 days, most of the healthy plants had two roots. Those with one or three roots, and particularly those which later

TABLE 2

AVERAGE NUMBER OF SEMINAL ROOTS PER PLANT IN CULTIVATED FORAGE GRASSES

	Agropyron cristatum			*Agropyron pauciflorum*			*Bromus inermis*		
Days after emergence	5	15	30	5	15	30	5	15	30
No. plants studied	65	43	28	78	47	21	63	31	12
Average No. seminal roots per plant	1.6	2.6	2.4	1.5	1.2	1.1	2.3	2.0	2.0

TABLE 3

VARIATIONS IN THE NUMBER OF SEMINAL ROOTS PER PLANT IN CULTIVATED FORAGE GRASSES AT DIFFERENT STAGES OF DEVELOPMENT

	Agropyron cristatum			*Agropyron pauciflorum*			*Bromus inermis*		
Days after emergence	5	15	30	5	15	30	5	15	30
No. plants studied	65	43	28	78	47	21	63	31	12
No. plants with one root	36	6	0	46	37	19	10	2	1
No. plants with two roots	22	21	20	23	10	2	28	26	10
No. plants with three roots	7	15	4	9	0	0	19	3	1
No. plants with four roots	0	1	4	0	0	0	6	0	0

gained the fourth root, were weak. At 30 days, those that had had one root had disappeared, a few plants with three roots were gaining strength, and those with four roots were dying. Only the plants with two roots were vigorous.

The condition in *Agropyron pauciflorum* was somewhat different. Of the seedlings five days old, 59% had one seminal root, 29.5% had two roots, and 11.4% had three. By 15 days, 78.7% of the plants possessed one root; 21.3% had two roots; but none had three. At 30 days, 90.5% of the total population had one root and only 9.5% two roots.

The behaviour of *Bromus inermis* differed from that of either of the preceding species. Only 15.9% of the plants at five days had one root, 44.4% had two, 30.2% had three, and 9.5% had four. The number of plants with one root decreased to 6.5% at 15 days; the number with two increased to 83.7%; those with three roots decreased to 9.7%; and there were none with four. At 30 days, plants with one root constituted 8.3% of the surviving population, those with two roots 83.3%, and those with three roots 8.3%.

At the five-day stage, plants with one root were most vigorous in *Agropyron pauciflorum*, followed by *Agropyron cristatum* and *Bromus inermis*. The seedlings with one root in *Agropyron pauciflorum* maintained their superiority over other classes until the 30-day stage. The same was true of plants of *Bromus inermis* with two roots. In *Agropyron cristatum* a second root was

developed by each vigorous plant after the five-day stage. The greatest variation in number of seminal roots per plant was found in material excavated five days after emergence. At 15 days the variation was less pronounced, and at the end of the first month of growth the number of seminal roots was practically stabilized in each species. The stabilization was achieved either by gain of an additional root in plants with one original root, or by the death of seedlings with three or more initial roots.

These observations indicate that in small-seeded forage grasses, unlike large seeded annual cereals, a large number of seminal roots per plant is a disadvantage. The reason for this is unknown. It may be that a large number of seminal roots exhausts the limited food reserves before sufficient leaves are developed to provide nourishment for the plant.

The number of seminal roots produced and the survival of seedlings were related to the depth from which the plants emerged. Practically all seedlings emerging from a depth greater than one-half inch produced an excessive number of seminal roots and perished either before two weeks of growth or soon after. Similarly, plants germinating on the soil surface were very weak and mostly died during the first month of growth, although they usually had fewer seminal roots. Seeds germinating between the soil surface and a depth of 0.5 inch produced vigorous plants with the normal number of seminal roots. A firm seed-bed with sufficient soil moisture is essential for normal development of the seminal roots of these grasses. Unsatisfactory stands of these grasses are primarily due to failure to provide a firm seed-bed, thus making it almost impossible to place the seed at the optimum depth. Firm soil, moreover, enables the delicate roots to come into contact with the moist soil particles, and thus insures them against desiccation before they penetrate to lower depths.

Nodal Root System

Each plant after being firmly established in the soil by the seminal root system, also developed numerous roots from nodes of the underground stem. The nodal roots of perennial grasses differ from the seminal roots in several respects. Morphologically, they usually possess swollen bases, whereas seminal roots always are of the same diameter from the base to the root tip. As a rule, nodal roots are of greater diameter than the seminal roots. Most important, however, is the fact that the former appear in greater numbers than the latter. While the number of seminal roots per plant is undoubtedly a genetic character and, therefore, more or less constant, the number of nodal roots depends mostly upon growing conditions. Plants of the same species sown on the same day and in similar soil, but supplied with different amounts of moisture, show very great differences in the number of nodal roots (Table 4). There were from 2.5 to more than 3 times as many on 60-day plants growing in moist soil as on those in dry soil. At three months the ratio had increased to about 4:1 for all species.

The first nodal roots appeared as tiny protuberances on the nodes of the underground stem when the seedlings were approximately 15 days old. From that time they developed rapidly and in ever increasing numbers (Table 5). These results were secured from plants spaced three feet apart. Under close competition there were fewer roots per plant, but they occurred in sufficient numbers to utilize available moisture completely.

TABLE 4

PRODUCTION OF NODAL ROOTS BY THREE PERENNIAL GRASSES IN ARID AND MOIST SOIL

	Agropyron cristatum		*Agropyron pauciflorum*		*Bromus inermis*	
	Arid	Irrigated	Arid	Irrigated	Arid	Irrigated
60-day plants	21	54	26	89	19	64
90-day plants	24	92	31	127	22	93

TABLE 5

NUMBER OF NODAL ROOTS PER PLANT OF THREE CULTIVATED GRASSES AT DIFFERENT STAGES OF DEVELOPMENT

Days after emergence	15	30	60	90	660	800
No. of plants studied	50	50	50	50	2	2
Agropyron cristatum	2	5	51	84	367	1431
Agropyron pauciflorum	4	10	91	124	951	870
Bromus inermis	2	9	61	83	1154	1315

Distribution of roots in the surface soil, their branching habits, and longevity are the main characters determining the responses of grasses to soil type and climatic conditions. Longevity of the nodal roots is particularly important. In *Agropyron pauciflorum*, the nodal roots were short lived although the crown persisted as long as four years. In *Bromus inermis*, they lived much longer; and in *Agropyron cristatum*, the crowns and the nodal roots regenerated readily and persisted almost indefinitely. In all cases, nodal roots were the last organs to stop functioning when a mature individual died. These roots penetrated to depths ranging from two to seven feet or more, the depth depending on the species, soil type, and soil moisture. Because of the great number per plant, they occupied the soil so completely that only a few species of forbs (broad leaved weeds) with very deep taproots could grow successfully with these grasses. Top soil was bound by the grass roots into a continuous carpet-like mat capable of resisting violet winds and the cutting action of water (30, 41, 59, 61). Their role in controlling soil erosion is therefore of great practical significance.

There was a gradual increase in the extent and penetration of the root systems of the three grasses during the first season of growth, and during the second year they grew with amazing rapidity (Table 6; Figs. 1–8). This spectacular expansion of roots was correlated with development of tillers and foliage. Three-year-old plants of *Agropyron cristatum* were 58 cm. high and had produced about 1,700 tillers. The seminal roots were dead or had been completely lost in the mass of nodal roots. The nodal roots on the other hand, were vigorous and showed evidence of making further increase in number. One plant had 274 young roots only 0.5 to 12 cm. long, intermingled with 722 functioning old roots. Altogether the nodal root system of this specimen consisted of 996 individual roots of various lengths. Eight of these

TABLE 6

DAILY INCREASE IN CM. OF THE ROOT SYSTEMS OF *Agropyron cristatum*, *Agropyron pauciflorum*, AND *Bromus inermis* AT VARIOUS STAGES OF PLANT DEVELOPMENT

Interval in days	0 to 5	5 to 15	15 to 30	30 to 60	60 to 90	90 to 435
Length of interval	5	10	15	30	30	165*
Agropyron cristatum	7	7	169	4,476	6,840	310,088
Agropyron pauciflorum	8	24	263	4,797	7,980	170,979
Bromus inermis	6	7	175	4,051	6,485	141,809

* *Development was greatly retarded or ceased entirely 180 days during fall, winter and spring between the first and second seasons of growth. Hence the interval of development was 165 days (345 — 180 = 165).*

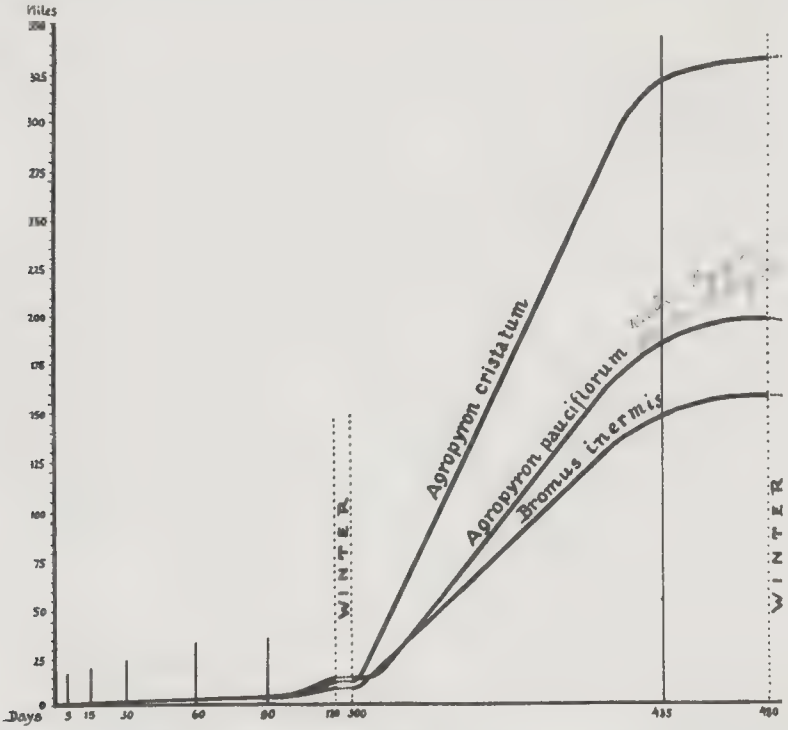
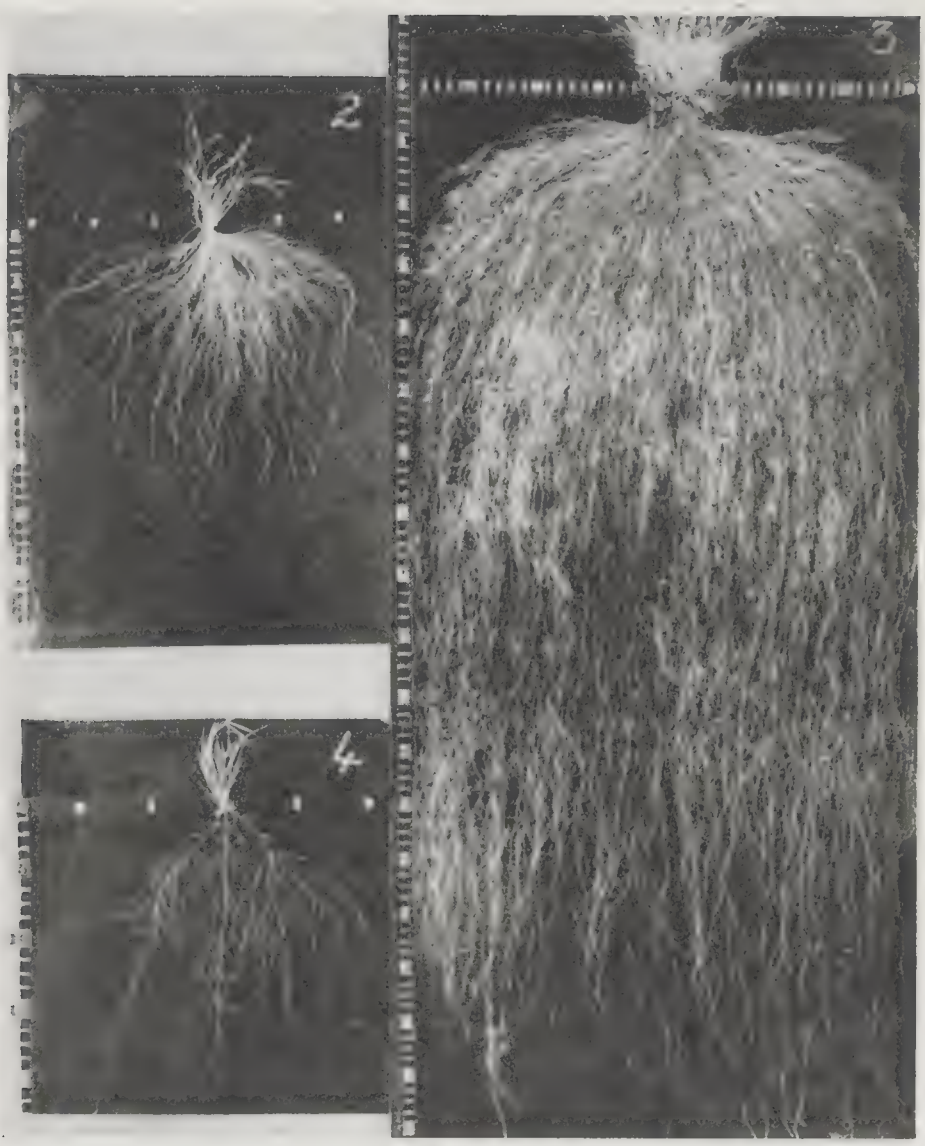


FIG. 1. *Total length in miles of roots of crested wheat grass (Agropyron cristatum), slender wheat grass (A. pauciflorum), and smooth brome grass (Bromus inermis) during the first and second year of growth. All increased gradually during the first season, but developed rapidly during the second year.*

roots penetrated to a depth of 250 cm. The total length of the nodal roots without branches was 1,025 metres. They produced 73,535,671 branches of all orders. The total length of the entire root system was 360.5 miles (Fig. 9).

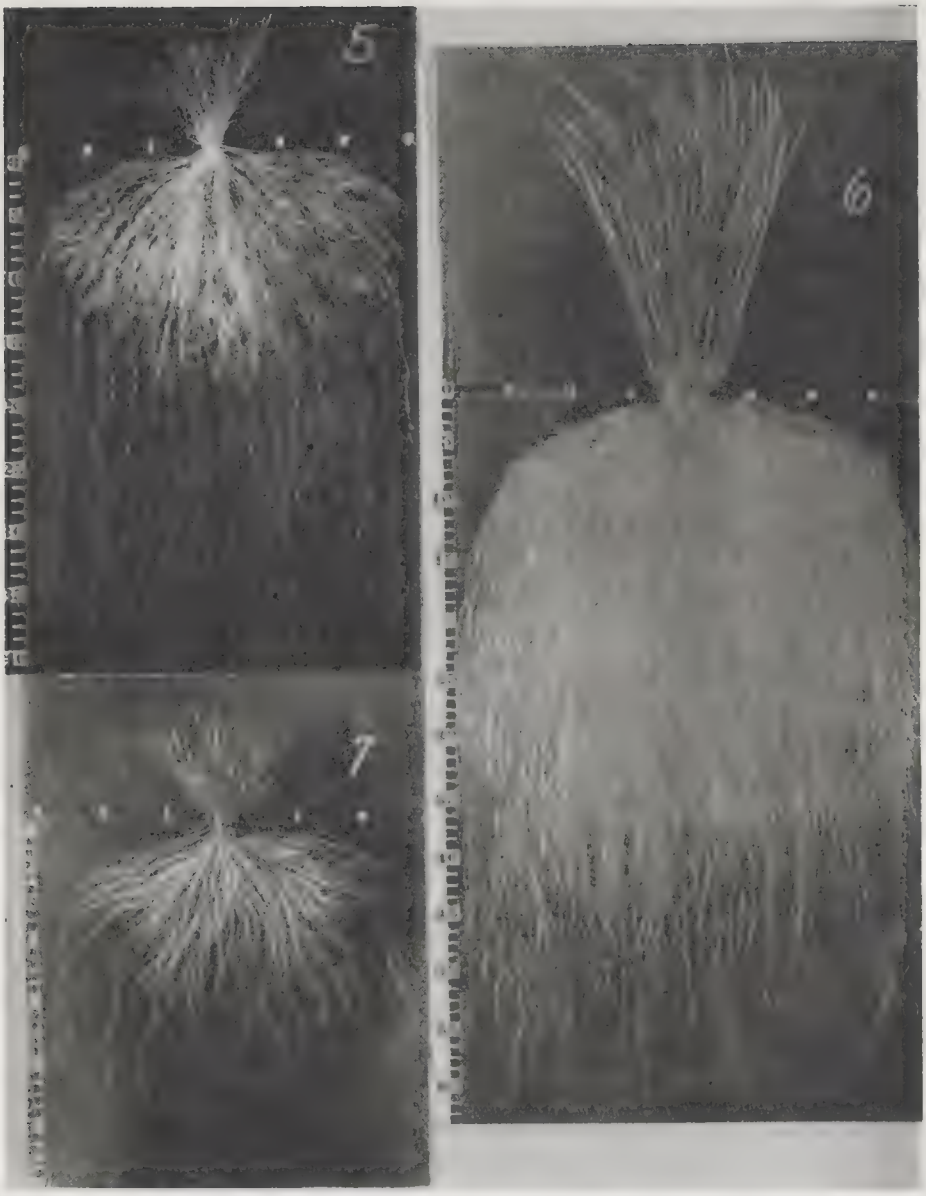
The extent of fine root structures was amazing. Root branches about one-tenth of a millimetre in diameter penetrated through hard soil a distance of 185 cm. or more, and from their points of departure from main roots they developed 600 to 700 still finer branches. One nodal root with its branches,



FIGS. 2 – 4. FIG. 2. *Roots of an isolated plant of Agropyron cristatum; total length at 90 days after emergence, 2.19 miles; maximum penetration about 32 inches.* FIG. 3. *Roots of two-year-old plant of A. cristatum; total length 320.1 miles (146 times total length for first season); depth of penetration, 7.5 feet.* FIG. 4. *Roots of Agropyron pauciflorum grown free from competition. They are well branched and nearly two feet deep although only two months old. Total length, 0.92 mile.*

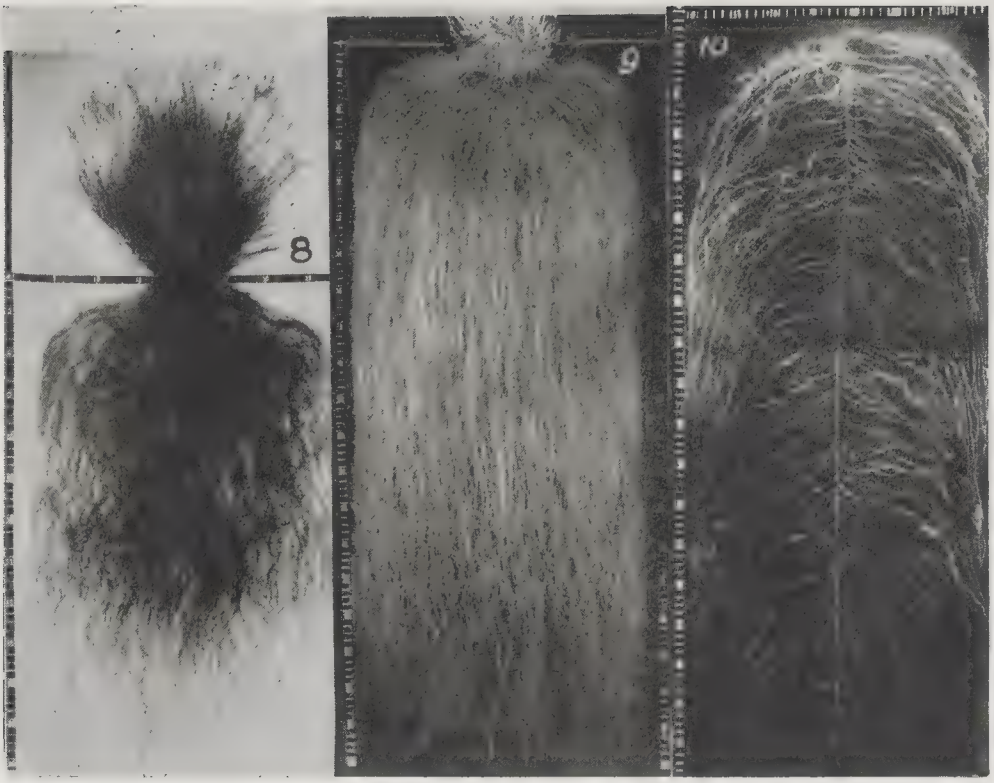
isolated from the system of a two-year-old plant of *Agropyron cristatum*, attained a total length of 17.71 miles (Table 7; Fig. 10). Two hundred and sixteen hours were required to measure and describe this root.

The root system of *Agropyron pauciflorum* developed more rapidly during the first season of growth than those of *A. cristatum* and *Bromus inermis*



FIGS. 5 – 7. FIG. 5. *Spaced plant of Agropyron pauciflorum, 90 days after emergence. Total length 2.4 miles, depth 40 inches. Greater length and penetration than crested wheat grass and smooth brome grass of equal age.* FIG. 6. *Two-year-old root system of A. pauciflorum. Total length 177.7 miles (55% of length of crested wheat grass root system of same age).* FIG. 7. *Root system of Bromus inermis, 90 days after emergence. Total length 1.9 miles. Rate of growth less than that of crested wheat grass and slender wheat grass during the first year.*

(Table 6; Figs. 1, 4, and 5). *Agropyron cristatum* took the lead the second year and exceeded *Bromus inermis* more than 2 to 1. It produced 3,100 metres of roots per day during the season of active growth while *Agropyron pauciflorum* developed 1,709 metres and *Bromus inermis*, 1,418 metres. Rates



FIGS. 8 – 10. FIG. 8. *Root system of Bromus inermis excavated at the end of the second summer. Length 147.4 miles.* FIG. 9. *Agropyron cristatum excavated at end of third summer of growth. Length 360.5 miles.* FIG. 10. *One nodal root (17.7 miles long) from a two-year-old plant of Agropyron cristatum.*

of daily increase were calculated only for the number of days the plants were vegetatively active.

ROOT DEVELOPMENT IN SODS

The number of roots per plant of all species was extremely low compared with the number of roots produced by the specimens widely spaced. In *Agropyron cristatum* as many as 1,865 nodal roots per spaced plant were recorded, but only 12 to 23 roots were found in plants grown in sod. The largest number of roots on a singly spaced plant of *A. pauciflorum* was 951, but there were only 6 to 14 in sod. Similarly, the largest number of nodal roots on a spaced plant of *Bromus inermis* was 1,315, but only 39 on a plant in sod.

The depth of roots of plants grown in sod was much less than that of spaced ones (Table 8). The difference was most pronounced in *Agropyron cristatum*. Number and length of root branches of all orders were greatly restricted in sod. In spaced plants of *A. cristatum* root branches reached a length of 185 cm., in *A. pauciflorum*, 105 cm., and in *Bromus inermis*, 115 cm. In sod of the same age the longest branch of *Agropyron cristatum* was only 49 cm., that of *A. pauciflorum* was 23 cm., and in *Bromus inermis* a length of 34 cm. was attained. Differences in the number of branches per plant were still greater.

TABLE 7

DETAILED DIMENSIONS IN CENTIMETRES OF ONE NODAL ROOT ISOLATED FROM THE ROOT SYSTEM OF *Agropyron cristatum* GROWN FOR TWO SEASONS IN AN AREA THREE FEET SQUARE

Depth (cm.)	Length of main root (cm.)	Branches of first order					Branches of second order					Length of main root and branches
		Number	Frequency per cm.	Maximum length	Ave. length	Total length	Number	Frequency per cm.	Maximum length	Ave. length	Total length	
– 12.5	12.5	80	6.4	134	94	7,520	50,640	6.8	20	3	151,920	159,452
12.5 – 25.0	12.5	72	5.8	163	104	7,488	55,720	7.5	28	5	278,900	286,401
25.0 – 37.5	12.5	65	5.2	158	109	7,085	52,925	7.5	33	10	529,257	536,354
37.5 – 50.0	12.5	60	4.8	185	112	6,720	42,520	6.3	30	11	467,720	474,453
50.0 – 62.5	12.5	60	4.8	155	96	5,760	36,060	6.3	30	11	397,949	403,721
62.5 – 75.0	12.5	50	4.0	147	89	4,450	25,440	5.8	28	9	228,960	233,423
75.0 – 87.5	12.5	47	3.8	137	81	3,807	18,800	5.0	28	9	169,290	173,109
87.5 – 100.0	12.5	47	3.8	129	36	1,692	10,177	6.0	25	8	88,916	90,621
100.0 – 112.5	12.5	47	3.8	132	43	2,021	10,345	5.2	25	8	82,760	84,793
112.5 – 125.0	12.5	47	3.8	124	61	2,876	11,520	4.1	20	8	92,160	95,040
125.0 – 137.5	12.5	47	3.8	104	73	3,431	13,005	3.9	23	8	104,040	107,483
137.5 – 150.0	12.5	40	3.2	86	68	2,720	9,600	3.6	20	8	76,800	79,533
150.0 – 162.5	12.5	40	3.2	81	58	2,320	8,160	3.6	16	5	40,800	43,132
162.5 – 175.0	12.5	40	3.2	66	56	2,220	6,930	3.2	16	5	34,650	36,883
175.0 – 187.5	12.5	35	2.8	56	48	1,680	6,792	3.6	13	5	30,713	32,405
187.5 – 200.0	12.5	35	2.8	38	30	1,050	5,966	3.2	8	2.5	11,258	12,321
200.0 – 212.5	12.5	35	2.8	38	23	805						817
212.5 – 225.0	12.5	30	2.4	33	15	450						463
225.0 – 237.5	4.0											4
Total	229.0					64,086					2,786,093	2,850,408 cm. = 17.71 miles

TABLE 8

EFFECT OF COMPETITION UPON DEPTH (CM.) OF ROOTS OF PERENNIAL GRASSES AT DIFFERENT STAGES OF DEVELOPMENT

Age	*Agropyron cristatum*		*Agropyron pauciflorum*		*Bromus inermis*	
	Sod	Spaced	Sod	Spaced	Sod	Spaced
5 days	7	12	9	14	6	10
15 days	11	17	14	19	10	15
30 days	21	37	28	43	19	34
60 days	44	75	54	88	47	61
90 days	62	82	67	102	63	82
2 years	114	246	122	140	104	163
4 years	119	226	124	145	107	157

The quantity of underground material produced by *Bromus inermis* after two years of growth (2,048.9 kilograms per acre) was greater than the amount produced either by *Agropyron cristatum* (1,805 kg.) or by *A. pauciflorum* (1,365.8 kg.). There was less root material in the sod of brome grass at the 15 to 30.5 cm. depth than in that of the other two species, but production was somewhat greater in the surface 15 cm. and much greater at the depth ranging from 30.5 to 152 cm. (Table 9). At the end of four years, underground material at all depths in plots of *Agropyron cristatum* exceeded that of *Bromus inermis* by 1.082.1 kilograms per acre, and that of *Agropyron pauciflorum* by 2,378.4 kilograms per acre. Yield in the surface 15 cm. in four-year-old sods of *A. cristatum* was more than three times that in two-year-old sods, and in the 30.5 to 152 cm. layer it was about twice as great. Yield in the intermediate layer, however, was less than half that of two-year sods. The marked increase in the upper layer of soil was attributed to increase in diameter of roots and crowns. *A. pauciflorum* doubled its yield in the surface 15 cm. during the third and fourth year, but showed marked decreases in the lower layers. The yield at all depths was only slightly increased between the second and fourth year. There was a consistent increase of material at all depths in *Bromus inermis*. Increase in the surface layer was correlated with increase in rhizomes. Yields of underground parts of these grasses per acre-foot generally agreed with those obtained by the Dominion Forage Crops Laboratory at Saskatoon, except in two-year sods of *Agropyron cristatum* and *Bromus inermis* (Table 10).

The span of life of root tissue and its physical properties varied with the species. This was shown by the quantity and quality of dead fibre of *Agropyron cristatum* and *A. pauciflorum* left in the soil three years after the sods had been broken (Table 11). The roots of the former withstood decomposition while many of the latter had become dust. The quantity of fibre remaining in soil previously occupied by *A. cristatum* was more than 33% greater than in soil that had supported *A. pauciflorum* (Fig. 11). Plots of *A. cristatum* successfully resisted soil drifting for six years after the sod was broken. Plots of *A. pauciflorum*, on the contrary, eroded badly one year after breaking, and in later years showed no more resistance to action of wind than land which had been continuously in grain.

TABLE 9

DISTRIBUTION OF UNDERGROUND PLANT MATERIAL IN SODS OF PERENNIAL GRASSES

(Oven-dry weight at 100° C.)

Depth (cm.)	Two-year-old sod			Four-year-old sod		
	Gm. per block	Kg. per acre	Per cent of total	Gm. per block	Kg. per acre	Per cent of total
Agropyron cristatum						
0 to 15	45.5	792.7	43.9	146.0	2,543.9	67.1
15 to 30.5	29.5	514.0	28.5	14.0	243.9	6.4
30.5 to 152	28.6	498.3	27.6	57.5	1,001.8	26.4
0 to 152	103.6	1,905.0	100.0	217.5	3,789.6	100.0
Agropyron pauciflorum						
0 to 15	37.8	658.6	48.2	70.5	1,228.3	87.0
15 to 30.5	20.0	348.4	25.6	5.5	95.8	6.8
30.5 to 152	20.6	358.9	26.2	5.0	87.1	6.2
0 to 152	78.4	1,365.9	100.0	81.0	1,411.2	100.0
Bromus inermis						
0 to 15	55.0	958.3	46.8	79.0	1,376.4	50.8
15 to 30.5	15.0	261.3	12.8	23.5	409.4	15.1
30.5 to 152	47.6	829.3	40.4	52.9	921.7	34.0
0 to 152	117.6	2,048.9	100.0	155.4	2,707.5	100.0

TABLE 10

AMOUNT OF UNDERGROUND MATERIAL PRODUCED BY THREE PERENNIAL GRASSES

(Kilograms per acre-foot)

	Agropyron cristatum		*Agropyron pauciflorum*		*Bromus inermis*	
Age (years)	2	4	2	4	2	4
Laboratory of Forage Crops, Saskatoon	1,766.2	2,649.0	895.4	1,149.0	1,700.0	—
Laboratory of Plant Ecology, Saskatoon	1,306.7	2,787.8	1,007.0	1,324.1	1,219.6	1,786.8

Quantity and Quality of Root Material

METHODS

Blocks of sod or soil 0.5 sq. metres in area and 10 cm. deep, were obtained from regions where the species grew naturally or, in the case of crop plants, where the species were well adjusted to the climate. Samples were representative of the density and vigour of vegetation in the respective regions. Sods of *Agropyron cristatum*, *A. pauciflorum*, and *Bromus inermis* were secured

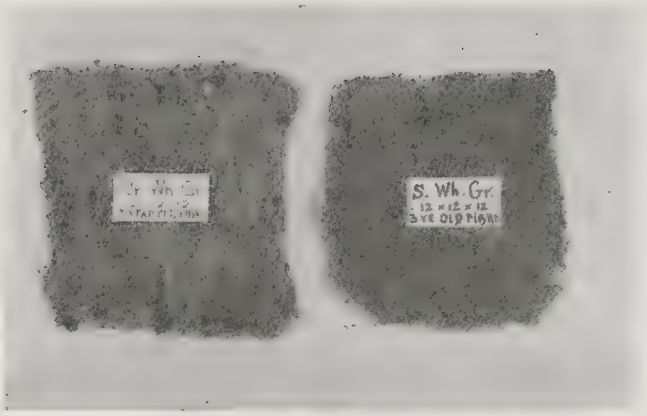


FIG. 11. *Fibre obtained from one cubic foot of soil broken three years before date of sampling from sod of crested wheat grass (left) and slender wheat grass (right).*

TABLE 11

AMOUNT OF DEAD FIBRE IN SOIL THREE YEARS AFTER BREAKING OF SOD

Depth (cm.)	Size of sample (cm.)	Oven-dry wt.		Combustible material	
		Gm.	Kg. per acre	Gm.	Kg. per acre
Agropyron cristatum					
0 – 15.0	30.5 × 30.5 × 15	64.6	2,814	54.4	2,369
15 – 30.0	30.5 × 30.5 × 15	34.6	1,507	29.5	1,272
0 – 30.0	30.5 × 30.5 × 30	99.2	4,321	83.9	3,641
Agropyron pauciflorum					
0 – 15.0	30.5 × 30.5 × 15	48.4	2,108	38.2	1,663
15 – 30.0	30.5 × 30.5 × 15	15.5	675	12.0	522
0 – 30.0	30.5 × 30.5 × 30	63.9	2,783	50.2	2,185

from four-year-old hay fields near Saskatoon; *Andropogon scoparius* was obtained from upland prairie in western Iowa; and the remaining species were from near Lincoln in eastern Nebraska. The sod of *Poa pratensis* was taken from a pastured ravine where it had produced a thick continuous stand; that of *Sporobolus cryptandrus* was taken from a pasture; and that of *Andropogon furcatus* was secured in lowland prairie. The sod of *Agropyron smithii* was selected from an extensive area of upland prairie which it had invaded after *Andropogon scoparius* was killed by a recent drought. Sods of *Bouteloua gracilis* and *Stipa spartea* were secured from upland prairie. Root material of common winter wheat was excavated from a field of normal stand. The root material of alfalfa was obtained from a four-year-old stand located on lowland where, for many years, it had been a successful crop.

The excavations were made in June, 1938. The blocks of sod were brought at once to the greenhouse, placed under water in tanks, and the earth washed from the roots by a stream of water from a fan-shaped nozzle mounted on a $\frac{3}{4}$-inch garden hose. Materials were washed under water to reduce the force

from the tiny jets of the nozzle. Even the root structures which were dead remained undamaged (Fig. 12). When clean, they were immediately placed in a 4% solution of formaldehyde. The root samples secured in the United States and Canada were washed again in a large tank illuminated so well that the slightest particles of soil could be detected and removed.

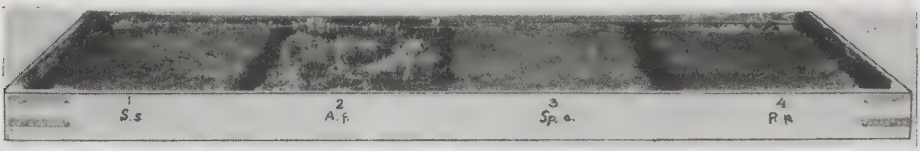


FIG. 12. *Root material of Stipa spartea (1), Andropogon furcatus (2), Sporobolus cryptandrus (3) and Poa pratensis (4), free of earth and floating in water.*

The material secured from each sod was carefully separated into three classes consisting of rhizomes and crowns, main roots, and branches. The quantity of each class was expressed in oven-dry weight at 100° C. The length of rhizomes and bases of culms was determined by actual measurement.

The number of branches of each order was calculated by the method described in the preceding section. The lengths of individual branches of any order were recorded one by one until the sum total of these lengths attained 10,000 cm. The quotient obtained by dividing 10,000 by the actual number of the branches which produced this length, was considered the mean length of branches of that order. The total number of branches of any order per block multiplied by their mean length gave their total length.

An instrument was constructed to measure the tensile strength of roots. This instrument consisted of two strong wooden plates lined with soft rubber strips upon the squeezing surfaces. The plates were fastened together by a joint pin at one end and had an extension screw at the other. One plate was permanently mounted on a stand by wooden screws and the other remained movable by the operation of the extension screw. When the plates moved apart, a piece of root 4 cm. long was inserted between their surfaces. When they were moved together by the extension screw, the root was caught between the rubber strips where even the tenderest roots were held firmly without damage. The hanging end of the piece of root was caught by an alligator clip, also lined with plastic rubber. The clip was tightened by means of a brass screw which fitted into a brass ring that slipped over the clip. A funnel-shaped pan provided with four sharp hooks was attached to the lower end of the alligator clip, and a linen sack was suspended from these hooks.

Fine sand was poured into the linen sack through the pan until the root broke. The weight of the clip, pan, and linen sack, together with the weight of the sand, recorded in grams, was taken as the index of tensile strength of the root. The results of ten or more tests of the root fibres of the same class gave a mean value which was taken to be the tensile strength of that particular class of roots. Roots which had been preserved in 4% formaldehyde solution were used for all determinations. The tensile strength was correlated with the diameter of the root. Diameters were accurately determined with the aid of a micrometric scale inserted in the ocular of a Zeiss microscope. The values obtained were in each instance the mean of ten representative samples.

The soil-binding equivalents of the rhizomes and the several ranks of roots were calculated by multiplying their respective tensile strengths (in grams) by their respective average lengths (in centimetres) per cubic centimetre of soil. Underground materials of each species were procured from 50,000 cc. of soil and the average lengths per cubic centimetre were obtained by calculation. The sum of the soil-binding equivalents of all underground parts of a species is the soil-binding equivalent of that species.

Dry Weight and Length of Roots and Rhizomes

Lengths and weights of underground stems are comparatively small (Table 12). The linear production of *Agropyron smithii* (209.2 miles per sq. metre, 20 cm. deep) was nearly two and one-half times that of its nearest competitor, *Bromus inermis* (Fig. 13). *Andropogon furcatus* and *Agropyron cristatum* gave the highest yields in weight with 1,246.5 and 1,243.2 kg. per acre, respectively. Wheat produced the least with only 213.7 kg. per acre.

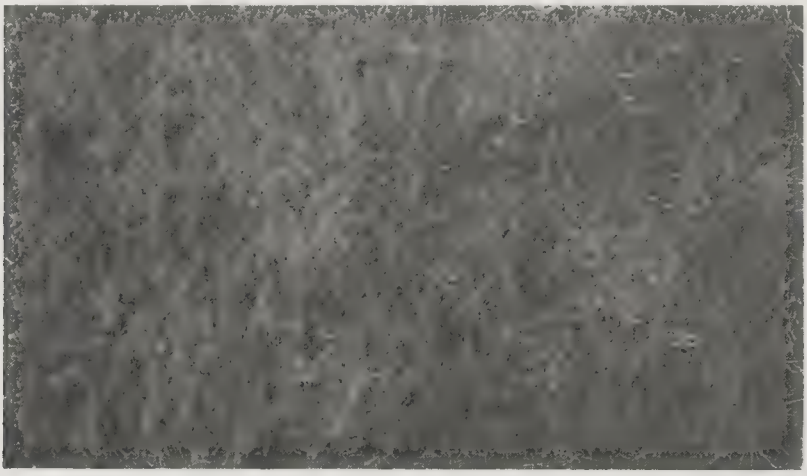


Fig. 13. *Coarse network of rhizomes of western wheat grass (Agropyron smithii) brought to the surface by breaking sod.*

Underground stems play a significant role, however, in production of new roots and stems which take active part in competition for moisture, nutrients, and light. They also serve as a coarse framework which holds the soil in place. Winter wheat and alfalfa, having no rhizomes and producing only 2 to 4 and 2 to 12 buds per crown respectively, bind the soil less firmly than do perennial grasses with numerous culms and rhizomes. A single plant of *Agropyron cristatum* developed from 12 to 23 tillers when grown in a close stand but as many as 1,100 when spaced. *Bromus inermis* had 6 to 17 tillers in sod but 600 or more when spaced. *Agropyron pauciflorum* produced only 3 to 8 stems in a close stand, but plants spaced three feet apart developed as many as 700 stems. Prairie grasses varied widely in the number of buds produced.

Main roots exert considerable binding effect upon the soil. Their chief significance, however, rests in their ability to produce multitudes of branches. These penetrate the soil in all directions and come into direct contact with

TABLE 12

QUANTITY OF UNDERGROUND PARTS OF CERTAIN GRASSES AND ALFALFA FOUND IN THE UPPER 10 CM. OF SOIL. THE UNIT AREA IS ONE-HALF SQUARE METRE

	Agropyron smithii	*Andropogon furcatus*	*Andropogon scoparius*	*Bouteloua gracilis*	*Poa pratensis*	*Sporobolus cryptandrus*	*Stipa spartea*	*Agropyron cristatum*	*Agropyron pauciflorum*	*Bromus inermis*	*Triticum aestivum*	*Medicago sativa*
Underground stems												
Length (m.)	104.6	19.8	16.0	7.6	27.7	9.1	11.5	23.4	4.5	41.1	14.8	46.7
Weight (gm.)	58.2	154.0	97.8	39.0	108.6	43.0	39.0	153.6	41.9	125.5	26.4	102.9
Weight (kg. per acre)	471.1	1,246.5	791.6	396.6	879.0	348.0	315.7	1,243.2	339.1	1,015.8	213.7	832.9
No. buds per crown	–	–	–	–	–	–	3 to 57	12 to 23	3 to 8	6 to 17	2 to 4	2 to 12
No. buds per cm. of rhizome	0.1	0.6	0.8	–	0.05	1.3	–	–	–	0.3	–	–
Main roots												
Number	11,528.0	3,472.0	3,397.0	5,829.0	16,278.0	4,372.0	4,378.0	11,688.0	8,070.00	11,410.0	1,490.0	
Length (m.)	1,037.5	277.8	305.7	408.0	1,139.5	481.1	44,446.0	935.3	562.8	1,026.2	178.8	
Weight (gm.)	34.8	76.4	36.0	29.6	67.2	68.4	46.0	58.4	31.8	60.8	17.1	
Weight (kg. per acre)	281.7	618.4	291.4	239.5	543.9	553.6	372.3	472.1	257.4	492.1	139.2	
Branches, 1st order												
Number	630,961.0	108,600.0	244,584.0	489,600.0	1,937,000.0	1,049,280.0	109,647.0	654,000.0	529,739.0	617,317.0	81,650.0	5,372.0
Length (m.)	43,534.3	4,722.9	11,006.3	9,781.6	75,480.0	13,733.5	6,384.5	39,240.0	21,179.6	37,039.1	4,296.5	253.6
Branches, 2nd order												
Number	1,652,294.0	543,000.0	3,301,884.0	4,798,400.0	10,567,000.0	3,774,700.0	1,196,151.0	7,852,700.0	2,279,250.0	2,850,000.0	1,103,000.0	151,600.0
Length (m.)	52,873.4	11,614.0	16,493.5	10,090.0	95,084.4	16,498.6	8,373.1	54,968.9	15,955.0	9,500.0	15,442.0	4,851.2
Branches, 3rd order												
Number	3,721,138.0	2,267,600.0	4,952,626.0	–	–	–	1,509,905.0	3,135,300.0	1,149,230.0	–	833,900.0	737,600.0
Length (m.)	7,442.3	4,535.2	9,904.3	–	–	–	3,019.8	9,466.5	3,102.9	–	6,671.2	5,163.2
All branches												
Number	6,004,393.0	2,919,200.0	8,499,094.0	5,288,000.0	12,564,000 0	4,823,980.0	2,815,703.0	11,642,000.0	3,958,219.0	3,467,317.0	2,018,550.0	894,572.0
Length (m.)	103,850.0	20,872.1	37,404.1	19,871.6	170,564.4	30,232.2	17,777.4	103,675.4	40,237.4	46,539.1	26,409.7	10,268.0
Weight (gm.)	52.2	114.6	54.0	44.4	101.0	102.6	69.0	87.8	47.7	91.5	26.2	–
Weight (kg. per acre)	422.5	927.6	437.0	359.4	817.5	830.0	558.4	710.6	386.1	790.6	212.1	–
Total												
Length (m.)	104,992.1	21,169.7	37,725.8	20,287.2	171,731.6	30,722.3	18,234.9	104,634.1	40,804.8	47,607.1	26,603.3	10,314.8
Weight (gm.)	145.2	345.0	187.8	123.0	276.8	214.0	154.0	299.8	121.4	277.8	69.7	118.9
Weight (kg. per acre)	1,175.3	2,794.5	1,520.0	995.5	2,240.4	1,731.6	1,246.4	2,425.9	982.6	2,298.5	565.0	962.4
Weight ratio to winter wheat	2.1	4.9	2.7	1.8	4.0	3.1	2.2	4.3	1.7	4.0	1.0	1.7

the smallest soil particles. Unlike main roots, they are composed largely of young, actively absorbing tissue. The ability of the species to compete with associated plants depends most directly upon the number of these branches. Similarly, the value of a species for reclamation of worn-out lands and for the restoration of good structure to highly pulverized soil also depends upon the amount and strength of these small rootlets.

The exceedingly numerous fine roots of bluegrass (*Poa pratensis*), together with its rhizomes, form a very compact sod. Bluegrass exceeded all other species studied in total number of roots found in the upper 10 cm. of soil (Table 12). There were in a half square metre more than 12.5 million main roots and branches, which if placed end to end would have extended 106.7 miles. Bluegrass also ranked high in weight of underground material, being exceeded somewhat by big bluestem (*Andropogon furcatus*) and only slightly by crested wheat grass (*Agropyron cristatum*) and smooth brome grass (*Bromus inermis*).

The underground material of big bluestem was heavier than that of any other species, being nearly five times that of winter wheat (*Triticum aestivum*). Its length, however, was only about one-eighth that of bluegrass. Only blue grama grass (*Bouteloua gracilis*), needle grass (*Stipa spartea*) and alfalfa (*Medicago sativa*) had lower total lengths of underground parts in the surface 10 cm.

Little bluestem (*Andropogon scoparius*) developed more branches of the third order in the upper 10 cm. of soil than any other species (41). Western wheat grass (*Agropyron smithii*) had about 75% as many, and crested wheat grass 60% as many; but blue grama grass, bluegrass, sand dropseed (*Sporobolus cryptandrus*), and smooth brome produced no roots of the third order in the upper 10 cm. of soil.

Crested wheat grass rated highest among the cultivated perennial grasses both in linear production and in weight of underground materials. Both crested wheat grass and smooth brome grass compared well with highly efficient prairie grasses such as big bluestem and bluegrass. The linear production of slender wheat grass (*Agropyron pauciflorum*) exceeded that of many prairie species, but its yield in weight was nearly as low as that of alfalfa.

Winter wheat produced in dry weight 45% as much as *Stipa spartea*, 56% as much as *Bouteloua gracilis*, 48% as much as *Agropyron smithii*, and 57% as much as *Agropyron pauciflorum*. In length, the wheat fibre excelled that of *Stipa spartea*, *Bouteloua gracilis*, and *Andropogon furcatus*. Thus wheat ranked relatively high in quantity of fibre and was fairly efficient in competition with weeds. However, it is not the quantity but the quality of root fibre which determines the value of a plant in controlling soil erosion. Roots of wheat are of poor quality. Many of the finer root-branches die and decompose before the plants are mature. The main roots undergo the same process soon after the crop is harvested, and after a few months no binding fibre remains in the soil.

Tensile Strength and Soil Binding Equivalents

Tensile strength of underground stems, main roots, and branches of roots varied appreciably within a species and much more so between the same structures of unrelated species (Table 13). Tensile strength was in no way

correlated with differences in diameter of roots of unrelated species, but it increased directly with the diameter within the same species. The main roots of crested wheat grass had a mean diameter of 0.4 mm. and a tensile strength of 820 gm. The mean diameter of the main roots of slender wheat grass was greater (0.5 mm.), yet their tensile strength was less than half as great (389 gm.).

Rhizomes of little bluestem and roots of big bluestem exhibited the greatest tensile strength. Roots of bluegrass showed the least actual resistance to pulling forces. Their relative strength, however, in proportion to the very small diameter was greater than that of other species. Tensile strength of underground structures of winter wheat was very low.

High linear production of underground materials in western wheat grass and relatively great resistance of these to pulling, gave this species the highest soil-binding equivalent. The soil-binding equivalent of crested wheat grass was only slightly lower and that of big bluestem ranked third. Little bluestem, sand dropseed, and slender wheat grass were lowest among the perennial grasses and the soil binding equivalent of winter wheat was only about 29% as great as that of slender wheat grass.

Expression of tensile strength and quantity of roots in terms of soil-binding equivalents provides a uniform way to present results and renders easy the comparison of species. These values, obviously, vary with the age of the plants and with the localities in which they grow. Nevertheless, they give certain quantitative concepts as to resistance to erosion. By use of soil-binding equivalents, the plant producer can be guided in his choice of crops.

Effect of Underground Parts of Certain Grasses upon Soil Structure

All soils gradually lose their original structure under tillage unless precautions are taken (24, 31). Soil that is reduced to dust by farm implements in dry periods is easily caught by wind and still more easily carried by runoff water. Erosion by wind and water finally results in a loss of valuable top soil, the formation of gullies, and the deposition of silt. Pulverization usually goes hand in hand with the more dangerous process of depletion of root fibre. It is true that the annual grain crops deposit large amounts of root material in the soil every year. This fibre, however, is strong only as long as the plants live. Soon after harvest, the roots undergo rapid decomposition (53). Perennial grasses produce much stronger root fibre capable of binding the soil for a considerable length of time.

Methods

Soil samples from sods of *Agropyron cristatum*, *Agropyron pauciflorum*, and *Bromus inermis*, were secured from fields which had been under continuous wheat for seventeen years or under a wheat-oat rotation for the same length of time. Other samples were also taken from native sods of *Andropogon scoparius*, *Andropogon furcatus*, *Bouteloua gracilis*, and *Stipa spartea*. All the samples were taken at five levels (0 to 10 cm., 10 to 20 cm., 20 to 30 cm., 50 to 60 cm., and 80 to 90 cm.).

Considerable difficulty was experienced in expressing the differences in structural composition of the soils in easily comparable quantitative units. When the samples were dry, their structural differences were quite noticeable.

TABLE 13

DIAMETER (MM.) AND TENSILE STRENGTH (GRAMS) OF UNDERGROUND STEMS AND ROOTS AND SOIL-BINDING EQUIVALENTS OF ELEVEN GRASSES

Species	Base of culm			Rhizome			Main root			Branches of first order			Branches of second order			Branches of third order			Soil-binding equivalent of species
	Diameter	Tensile strength	Soil-binding equivalent	Diameter	Tensile strength	Soil-binding equivalent	Diameter	Tensile strength	Soil-binding equivalent	Diameter	Tensile strength	Soil-binding equivalent	Diameter	Tensile strength	Soil-binding equivalent	Diameter	Tensile strength	Soil-binding equivalent	
Agropyron smithii	2	—	—	2.1	2,882	576	.46	849	1,698	.18	79.4	6,906	.03	2	211	.018	.8	11	9,402
Andropogon furcatus	3.4	—	—	4.1	3,129	115	1.1	1,712	941	.23	623	5,856	.11	64	1,472	.05	2	18	8,402
Andropogon scoparius	2.4	—	—	2.2	5,678	176	.41	1,171	714	.1	31	672	.06	6	198	.02	2	39	1,799
Bouteloua gracilis	1.2	—	—	1.8	—	—	.31	757	613	.06	71.6	1,361	.02	7	140	—	—	—	2,114
Poa pratensis	1.4	—	—	1.3	1,864	92	.19	273	600	.04	9.7	1,464	.018	1.2	126	—	—	—	2,282
Sporobolus cryptandrus	2.1	—	—	1.9	568	10	.62	821	788	.07	17	459	.02	2.9	95	.006	1.5	—	1,352
Stipa spartea	1.7	712	16	—	—	—	.66	981	873	.21	294.9	3,775	.09	26	434	.028	4	24	5,122
Agropyron cristatum	1.4	1,002	46	—	—	—	.4	821	1,533	.09	88	6,899	.04	8	879	.01	1.3	24	9,381
Agropyron pauciflorum	1.6	583	5	—	—	—	.5	389	428	.1	19	774	.03	1.6	51	.007	.5	3	1,261
Bromus inermis	1.8	—	—	1.5	2,737	224	.6	651	1,302	.1	30.5	2,237	.04	6.4	121	—	—	—	3,884
Triticum aestivum	2	538	16	—	—	—	.32	533	182	.09	8	68	.03	3.3	99	.008	.8	10	375

Upon soaking, these differences were masked by dispersed clay, silt and sand. Structural aggregates of soils taken from different sods disintegrated in water at different rates. This led to the use of water for segregation of soil aggregates into structural fractions. For practical purposes, three such fractions were used. These were segregated on the basis of their sizes after they had passed through the pedostructometer described below. Fraction A contained aggregates 0.8 mm. or more in diameter; fraction B had aggregates of 0.6 to 0.8 mm. in diameter; and fraction C had aggregates that were less than 0.6 mm. in diameter. Special precautions were exercised with regard to two factors. First, the samples were subjected to a standardized force of water and second, this force was operated for the same length of time on each sample. Any differences in the size of the fractions secured were, therefore, attributed entirely to their specific resistances to the eroding action of water. A special apparatus, called a pedostructometer, was constructed for determining the structural condition of soil (Fig. 14).

Water in the pressure tank (t) was kept at a constant level (cl). Any lowering of the water level was automatically indicated on a scale (s) by the

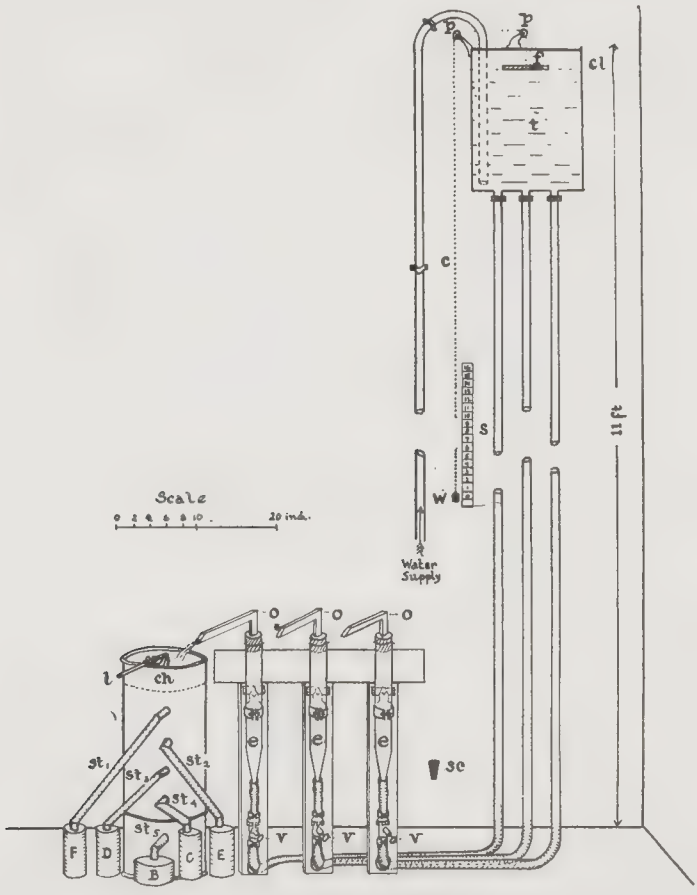


FIG. 14. *Pedostructometer, an instrument for determining the structural condition of soil. Description in text.*

rise of a weight (w) which was connected by a cord (c) and pulleys (p) with a wooden float (f). The bottom of the tank was connected by 0.75-inch rubber tubes with three separate 0.5-inch valves (v). Since the height of the water columns from line (cl) to each of the valves was the same, the water pressure at the valves was kept constant. The valves in turn were connected by rubber tubing with the elutriators (e). Latten screens (sc.) of 0.2 mm. mesh were tightly fitted into the cone shaped bottoms of the elutriators in order to prevent aggregates of larger diameter from falling beyond the bottom of the tubes. All elutriators were of the same diameter. They were closed by rubber corks with outlets of brass tubing 0.75 inch square inside.

A soil sample of 200 grams, oven-dry weight, was placed in each elutriator without modifying its original structure. As soon as the sample was in place, the valve (v) was opened slightly and water entered the tube (e) until the soil was covered. Then each sample was soaked for 15 minutes to simulate field conditions when soil is saturated with water. This treatment left all the structural aggregates of the soil sample free of any cementing effect by the colloidal fraction which operates strongly between structural units of dry soil. At the end of 15 minutes, the valve (v) was opened fully and 50 litres of water, under a pressure of 300 grams per square centimeter were passed through the elutriator (e). The resulting current approximated closely the force of runoff water on slopes of 10 degrees. This particular current was selected, because slopes of greater degree are of less agricultural importance.

Structural aggregates previously cemented together into larger lumps were gradually liberated by this current. The colloidal fraction and the clay and silt particles were first caught and carried away by the water through the outlet (o). Aggregates of increasing sizes followed in succession. When the 50 litres of water had passed through the elutriator, only those units which retained their large size and weight against the force of water throughout the entire process were left in the tube. This part of the sample was called fraction A. All the soil particles lighter in weight than that which was required to resist the lifting action of the water current in the elutriation tube were carried away with the water into the elutriation chamber (ch).

In the elutriation chamber, the soil particles fell to the bottom with different speeds, according to Stokes' law. On this basis, it was possible to subdivide them into five fractions. The height of the chamber was divided into five equal parts, each containing 10 litres of water. Sampling tubes (st_1, etc.) were inserted in the wall of the chamber at the lower end of each division. These were provided with special open-close devices, controlled by a lever (l), by means of which the contents of the chamber were sampled at the same moment at all five levels. Before sampling, the turbid water in the chamber was thoroughly agitated so as to put the particles of all sizes into suspension. Samples were taken two seconds after the stirring was stopped. During the two seconds of rest, the heaviest soil aggregates had dropped to the bottom, but lighter ones were suspended at various levels. The fractions of various sizes obtained from tubes st_5, st_4, st_3, st_2, and st_1 were then called fractions B, C, D, E, and F, respectively. Since fractions C, D, E, and F contained aggregates of small diameter generally found in highly pulverized soils, it was decided to bulk them into one composite, fraction, C. Samples of equal volume from the bulk samples of these fractions were reduced to oven-

dry weight, and weights of each fraction and average diameters of their aggregates were determined.

Results

The soil samples analysed by this method all belonged to the silt clay or silt-loam groups. The samples taken at Saskatoon contained less sand and more clay than those from Nebraska. The silt separates in both groups were high, fluctuating only within reasonably narrow limits of 51.36 to 60.07% (Table 14). The results from structural analyses are presented in Fig. 15.

TABLE 14

Textural separates, % of soil samples taken from sods of certain grasses

(Diameters of particles in mm.)

Species	Gravel and sand 2.0–0.05	Silt 0.05–0.005	Fine silt 0.005–0.002	Clay less than 0.002	Total silt-clay	Class of soil
Wheat-oat rotation for 17 years	21.01	32.22	26.17	20.09	74.48	Silt clay
Agropyron cristatum	12.02	19.17	37.57	31.21	87.95	Silt loam
Agropyron pauciflorum	17.28	26.29	27.44	28.73	82.46	Silt clay
Bromus inermis	16.36	19.91	35.12	28.60	83.63	Silt clay
Andropogon scoparius	34.83	52.27	4.34	8.66	65.27	Silt loam
Andropogon furcatus	39.43	43.24	9.33	8.00	60.57	Silt loam
Bouteloua gracilis	41.33	46.34	5.00	7.33	58.67	Silt loam
Stipa spartea	23.93	51.40	8.67	16.00	76.07	Silt loam

The data reveal very important differences, both in sizes of structural aggregates and in weights of the fractions (Fig. 15). In the sample obtained from the field of continuous wheat, fraction A constituted only 0.61% by weight of the total sample taken to a depth of 10 cm. In the wheat-oat rotation, it amounted to 0.52%; in *Agropyron cristatum*, 15.23%; in *Agropyron pauciflorum*, 0.16%; *Bromus inermis*, 2.09%; in *Andropogon scoparius*, 17.05%; in *Andropogon furcatus*, 20.84%; in *Bouteloua gracilis*, 18.21%; and in *Stipa spartea*, 14.21% of the total sample. Virgin soils contained from 14 to 20% of structural aggregates from 4 to 0.8 mm. in size. In fields under continuous cultivation, on the other hand, only approximately 0.5% of these aggregates remained intact.

In view of these two extremes, the data procured from sods of the three cultivated grasses are of practical interest. Plots of these grasses were established only five years previous to the sampling, on land which had been under continuous grain since 1911 and which was very similar to that representing the continuous wheat and wheat-oat rotation, with respect to type, location, and degree of pulverization. Important structural changes took place after five years. If fraction A of continuous wheat is taken as a unit, indicating a degree of soil structure under this system of farming, and compared with fractions A of *Agropyron cristatum*, *Agropyron pauciflorum*, and *Bromus inermis* sods, ratios of 1 : 25, 1 : 0.85, and 1 : 3.4, respectively, are obtained. *Agropyron pauciflorum* did not improve the soil structure. *Bromus inermis* increased the amount of the large soil aggregates nearly four times.

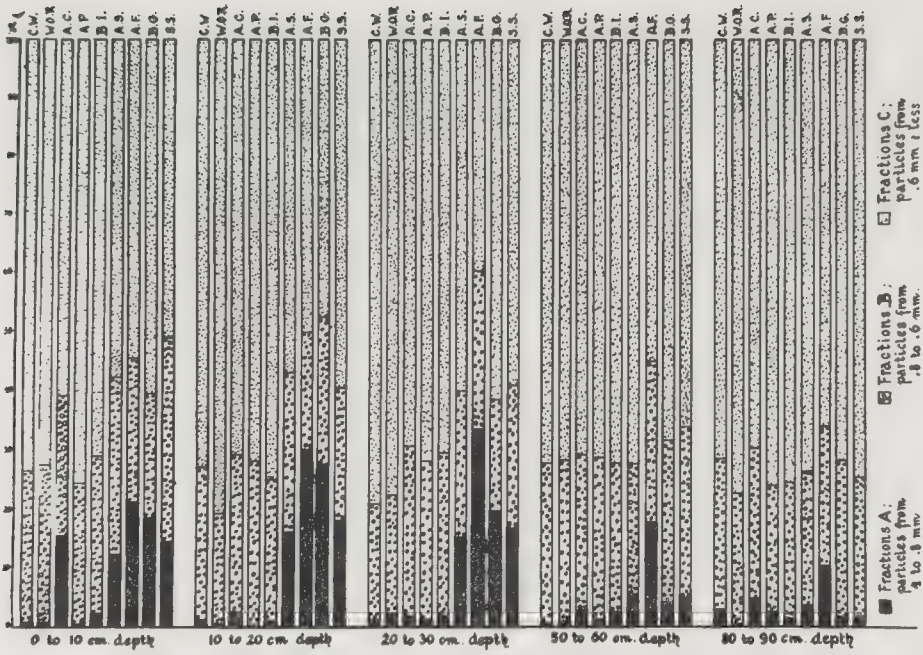


FIG. 15. *Structural analyses of soil samples taken at several depths from fields of cultivated and native perennial grasses and grain crops. Continuous wheat (C.W.); wheat-oats rotation (W.O.R.); Agropyron cristatum (A.C.); Agropyron pauciflorum (A.P.); Bromus inermis (B.I.); Andropogon scoparius (A.S.); Andropogon furcatus (A.F.); Bouteloua gracilis (B.G.); and Stipa spartea (S.S.).*

Agropyron cristatum was most effective, and in this topmost layer, restored the soil structure to the condition found in a sod of *Stipa spartea*. These profound differences in the condition of the top soil, brought about by the root material of the three cultivated grasses, were further seen in their freshly broken sods (Figs. 16–18).

Agropyron cristatum deposited so much strong root fibre in the top layer of the soil on both the light sandy loam and on a chocolate heavy loam that its sod broke into continuous furrow slices with highly granulated structure. *Bromus inermis* also produced good furrow slices, but the granular structure was much less pronounced. The furrow slices of *Agropyron pauciflorum*, however, were badly broken and did not manifest structure to any greater degree than those of any field under continuous grain.

At depths exceeding 10 cm., none of the cultivated grasses had an appreciable effect upon the soil structure. The soil samples taken from the virgin prairie, however, produced higher percentages of fraction A from depths 10 to 20 and 20 to 30 cm. than from the layer 0 to 10 cm. deep (Fig. 15).

Fraction C increased in proportion to the reduction of fraction A in soil subjected to extensive tillage under annual crops. Fraction B seemed to remain almost constant in both virgin and tilled soil. This is true only as far as quantity is concerned. In reality, the aggregates of this fraction were also reduced to fraction C by cultivation. This loss, however, was compensated for by the gain from fraction A. The fact that fraction A was high for all the species with high soil-binding equivalents seems to indicate that a close

FIGS. 16, 17. FIG. 16. *Freshly broken sod of crested wheat grass (Agropyron cristatum) on light sandy loam. Furrow slices, bound by grass roots, have remained intact.* FIG. 17. *Freshly broken sod of slender wheat grass (Agropyron pauciflorum) on light sandy loam. Roots failed to hold the soil and the furrow slices are broken.*

relationship exists between the amount and strength of root material of each species and their ability to restore the structure of highly pulverized soils. The depth of penetration of the root systems also seems to play an important part in this respect. This may be illustrated by the samples obtained from *Bouteloua gracilis* and *Andropogon furcatus* (Fig. 15). *Bouteloua gracilis* has

FIG. 18. *Newly broken sod of smooth brome grass (Bromus inermis) on light sandy loam. Roots were sufficiently numerous to keep the furrow slices intact.*

a dense system of very fine, yet strong, fibrous roots. These penetrate only to a depth of 45 to 60 cm. The first 30 cm. below the surface is well supplied with its root fibre. Fraction A in the samples taken from 0 to 10 cm. made 18.21% of the entire sample; from 10 to 20 cm., it reached the value of 27.25%; at 20 to 30 cm., it dropped to 19.00%; and from 50 to 60 cm., to 3.70%; finally, at 80 to 90, it amounted only to 1.51% of the sample. This variation can be explained only by quantity of the roots at the various levels. The root system of *Andropogon furcatus*, on the other hand, is very strong and deep (57). Its main roots serve as a coarse, soil-binding framework, while the numerous finer branches provide an abundance of fibrous material which keeps the smaller soil aggregates together. Hence, it affected the soil structure to a greater depth than a grass with shallower roots.

The length of time the land had remained in sod was an important factor. Although root material of *Agropyron cristatum* has a higher soil-binding equivalent than *Andropogon furcatus*, yet fraction A of soil from *Agropyron cristatum* sod was only 15.23%, as compared with 20.84% for *Andropogon furcatus*. The sod of *Agropyron cristatum* was only five years old, while that of *Andropogon furcatus* was probably centuries old.

The soil-binding equivalent, together with depth of penetration, age and longevity of the root systems of various species, throws some light upon the ability of roots to improve soil structure damaged by a continuous grain farming or other destructive agencies. The differences, however, are hardly sufficient to explain the profound variations observed in the structure of soils remaining for a considerable time under their occupation. Probably products of decomposition of different roots and some other factors play an equally important part in the process of restoring the soil structure.

It may be concluded that a definite possibility exists of expressing the structure of any soil in quantitative units by means of structural analyses; that grass roots afford a practical means of restoring structure to highly pulverized soils; that the soil-binding equivalent and the depth of penetration of the root system of grasses are useful criteria in the selection of species for erosion control; and that further research along this line may provide valuable information with respect to practical problems of soil management.

Control of Annual Weeds

The ever increasing population of weed seeds in the soil under continuous grain farming has created a problem which is national in scope. Most common weeds mature and shatter seed before grain crops are harvested. On this account the ground is heavily polluted with weed seeds every year. A certain quantity of these seeds remains viable for more than one year (20). Thus, the population of weed seeds becomes increasingly greater. The situation often becomes so serious that farmers are compelled to employ extensive surface tillage to destroy the weeds. This, in turn pulverizes the soil and makes it susceptible to erosion. In view of the seriousness of this problem, the extent to which weeds might be reduced by keeping the land in sod of *Agropyron cristatum*, *A. pauciflorum*, and *Bromus inermis* was investigated.

The experiments were conducted on a heavy silt chocolate loam infested with one of the following annual weeds: *Sinapis arvensis* L., common wild mustard, *Avena fatua* L., wild oats, *Thlaspi arvense* L., penny-cress, and *Chenopodium album* L. lamb's quarters (Figs. 19–21).

This type of soil, with variations toward lighter sandy loams and heavier clays, makes up approximately 80% of the cultivated acreage in Western Canada and usually is associated with at least one of these important annuals (33).

Methods

Experimental plots, one square rod in size, were established on land which had been under grain farming for 26 years, was heavily infested with weeds, badly pulverized, and subject to drifting. They were first infested with one of the four weeds at rates equal to the amounts of seed produced and annually shattered by heavy infestation of the weeds. Accordingly, wild oats plots were seeded at a rate of 8 bushels per acre. Those of wild mustard, penny-cress, and lamb's quarters were sown at the rates of 3, 2.5, and 1 bushel per acre, respectively. The plots thus infested, as well as the controls, were then sown by broadcasting *Agropyron cristatum*, *A. pauciflorum*, and *Bromus inermis* at the rates of 25, 35, and 30 pounds per acre, respectively. The number of weeds and grasses was determined for three square-metre quadrats, taken at random, 24, 41, and 82 days after emergence, during the first season, but only once during the second, fourth, fifth, sixth, and seventh seasons of growth. All experimental plots were cut at the age of 70 days when the weeds were in blossom. Three groups of plots were used in this experiment. One of these groups was established in 1933, another in 1935, and the third in 1938.

Results

Rates of seeding for grasses were high, and uniform stands were secured. There was a gradual increase in grass population in control plots during the first season of growth (Tables 15, 16, 17, and 18).

FIGS. 19 – 21. FIG. 19. *Wheat field infested with wild oats (Avena fatua). This is a common weed in fields under continuous grain farming.* FIG. 20. *Wheat field, which has been overrun with wild mustard (Sinapis arvensis).* FIG. 21. *Penny cress (Thlaspi arvense) in a field of wheat. (Courtesy of the Dominion Experimental Station at Scott, Saskatchewan).*

TABLE 15

AVERAGE NUMBER OF PLANTS PER SQUARE METRE IN PLOTS WHERE CERTAIN PERENNIAL GRASSES WERE GROWN WITH *Avena fatua*

Species	No. of plots	Days after emergence			No. of plots	Year after emergence				
		24	41	82		2nd	4th	5th	6th	7th
Agropyron cristatum										
Control	9	8,606	11,183	13,601	3	7,499	7,142	6,687	6,443	3,125
Experimental crop	9	4,991	7,926	8,168	3	6,161	7,316	4,227	4,196	3,323
Wild oats		525	897	12		0	0	0	0	0
*Agropyron pauciflorum**										
Control	9	2,506	4,428	5,256	3	2,449	713	604	504	1,707
Experimental crop	9	1,993	2,246	1,521	3	2,169	631	502	436	678
Wild oats		600	834	59		0	0	0	0	0
*Bromus inermis**										
Control	9	2,528	4,348	5,793	3	2,738	2,689	2,678	2,660	2,014
Experimental crop	9	1,868	3,152	3,670	3	2,036	3,240	2,047	1,720	1,248
Wild oats		642	754	4		0	0	0	0	0

* *Volunteer weeds were present in all plots of Agropyron pauciflorum and Bromus inermis after the first year.*

TABLE 16

AVERAGE NUMBER OF PLANTS PER SQUARE METRE IN PLOTS WHERE CERTAIN PERENNIAL GRASSES WERE GROWN WITH *Sinapis arvensis*

Species	No. of plots	Days after emergence			No. of plots	Year after emergence				
		24	41	82		2nd	4th	5th	6th	7th
Agropyron cristatum										
Control	9	8,606	11,183	13,601	3	7,499	7,142	6,687	6,443	3,125
Experimental crop	9	3,900	5,345	4,777	3	6,212	5,890	4,366	4,373	3,019
Wild mustard		1,271	844	63		0	0	0	0	0
*Agropyron pauciflorum**										
Control	9	2,506	4,428	5,256	3	2,449	713	604	540	1,707
Experimental crop	9	1,801	2,473	385	3	1,911	512	342	293	700
Wild mustard		1,354	1,608	131		37	0	0	0	0
Bromus inermis										
Control	9	2,528	4,348	5,793	3	2,738	2,689	2,678	2,660	2,014
Experimental crop	9	1,695	3,133	3,505	3	2,213	2,076	1,432	1,490	1,508
Wild mustard		805	750	19		0	0	0	0	0

* *Volunteer weeds were present in all experimental plots of Agropyron pauciflorum and Bromus inermis after the first year and in control plots of Agropyron pauciflorum after the third year.*

While grasses established reasonably uniform stands in the experimental plots in the early seedling stage, they suffered appreciably during the latter part of the first season of growth. *Agropyron pauciflorum* was suppressed most, followed by *Bromus inermis* and *Agropyron cristatum*. *Sinapis arvensis* was the most efficient competitor of grasses, followed by *Chenopodium album*, *Thlaspi arvense*, and *Avena fatua*.

All species of weeds germinated earlier than the grasses and grew more rapidly after germination. They not only occupied the soil with their roots

TABLE 17

AVERAGE NUMBER OF PLANTS PER SQUARE METRE IN PLOTS WHERE CERTAIN PERENNIAL GRASSES WERE GROWN WITH *Chenopodium album*

Species	No. of plots	Days after emergence			No. of plots	Year after emergence		
		24	41	82		2nd	6th	7th
Agropyron cristatum								
Control	6	8,606	11,183	13,601	3	7,499	6,443	3,125
Experimental crop	6	5,997	8,225	8,978	3	8,048	4,453	2,919
Lamb's quarters		532	656	4		0	0	0
*Agropyron pauciflorum**								
Control	6	2,506	4,428	5,256	3	2,449	540	1,707
Experimental crop	6	1,270	1,884	326	3	2,899	530	628
Lamb's quarters		1,412	1,639	131		306	0	0
*Bromus inermis**								
Control	6	2,528	4,348	5,793	3	2,738	2,660	2,014
Experimental crop	6	1,717	2,600	3,026	3	2,004	1,810	1,304
Lamb's quarters		917	740	8		188	0	0

* *Volunteer weeds were present in all plots 6 and 7 years old.*

TABLE 18

AVERAGE NUMBER OF PLANTS PER SQUARE METRE IN PLOTS WHERE CERTAIN PERENNIAL GRASSES WERE GROWN IN COMPETITION WITH *Thlaspi arvense*

Species	No. of plots	Days after emergence			No. of plots	Year after emergence		
		24	41	82		2nd	4th	5th
Agropyron cristatum								
Control	6	8,606	11,183	13,601	3	7,499	7,142	6,687
Experimental crop	6	5,486	7,920	10,358	3	8,019	6,696	3,652
Penny-cress		2,051	1,718	73		0	0	0
*Agropyron pauciflorum**								
Control	6	2,506	4,428	5,256	3	2,449	713	604
Experimental crop	6	1,528	2,242	1,901	3	2,666	803	632
Penny-cress		1,821	1,038	133		203	0	0
*Bromus inermis**								
Control	6	2,528	4,348	5,793	3	2,738	2,689	2,673
Experimental crop	6	1,717	3,146	4,324	3	2,310	2,686	1,525
Penny-cress		1,582	855	0		28	0	0

* *Volunteer weeds occurred in all plots 4 and 5 years old.*

earlier than the grasses, but covered the surface with a rank growth of tops. Soon after the first counting, 24 days after emergence, weeds shaded the grasses so much that they suffered severely from deficiency of light (Fig. 22).

After 70 days, all experimental plots were cut close to the ground. In twelve days after cutting, grasses in all experimental plots took advantage of the removal of weeds and showed amazing recovery. *Agropyron cristatum* was in the lead, closely followed by *Bromus inermis* and *A. pauciflorum*.

FIG. 22. *Crested wheat grass, Agropyron cristatum, in control plot (left) and in competition with common wild mustard, Sinapis arvensis (right). Grasses in the experimental plot suffered severely from deficiency of light.*

Farmers often become discouraged by the presence of so many weeds in grass fields during the first season of growth and permit them to remain on the land and smother the weakened grasses. Mowing the weeds, however, makes possible quick and successful recovery of the crops.

During the second year of growth, all grasses took almost exclusive possession of the land. At the same time, there were readjustments both in the control and the experimental plots. While the grass in the experimental plots grew vigorously as soon as the spring opened, that in the control areas remained brown in colour and comparatively small until the end of May. This may be explained by the fact that stands of grass in some experimental plots were thin, and each plant had more moisture and light. In the controls and some experimental plots, where stands were thick, severe competition took place between the grass plants themselves. The count for this reason showed that where grass population was too high during the first year, it was drastically reduced. On the other hand, the count was relatively high in plots where stands had been thin because of competition with weeds (Figs. 23–25). The increase in number of stems resulted either from tillering or from germination of seed which had remained dormant during the first season.

The ability of the three grasses to control their habitats after they had become established may be seen from the results secured during the second to the seventh years of growth. *Agropyron cristatum* remained conspicuously free of weeds for the duration of this experiment, even in plots where stand was somewhat patchy. *Agropyron pauciflorum*, after producing an optimum stand and maintaining it for two seasons, deteriorated during the third year and gave way to annual weeds. *Bromus inermis* occupied an intermediate position between the other two grasses. It gained strength and maintained

FIG. 23. *Stand of crested wheat grass (Agropyron cristatum) during the second season of growth. This grass had competed with common wild mustard (Sinapis arvensis) during the first summer.*

a stand for a number of years after it became established. Finally, however, bare areas appeared and were claimed by annual weeds. A few volunteer weeds were recorded in the experimental plots of *Bromus inermis* as early as the second season of growth. Their numbers slowly increased until the seventh season when all the plots were considerably overrun.

Weeds which appear in bare areas in pastures and meadows or on abandoned lands are plants which thrive successfully only in habitats not annually disturbed by cultivation. Peppergrass (*Lepidium apetalum* Willd.) and fleabane (*Erigeron annuus* (L.) Pers.) are examples of this group. Presence of these weeds really does not seriously diminish the value of perennial forage grasses in controlling the annual weeds which are common under cultivation and highly injurious to grain crops.

This was clearly demonstrated by the results obtained from an experiment where seven-year-old sods of *Agropyron cristatum* and *A. pauciflorum* were broken and sown to wheat together with a similar series of plots established on regularly cultivated land. A clean crop was produced on sods of both grasses. The weeds of the grassland, which had been prevalent in the plots of *Agropyron pauciflorum*, had completely disappeared, and the weed seeds commonly found in cultivated fields had perished during the period that the land was in sod (Table 19).

FIGS. 24, 25. FIG. 24, *Slender wheat grass (Agropyron pauciflorum) during the second season of growth. Grasses in this plot were so suppressed the preceding year by wild mustard that they were difficult to find.* FIG. 25, *Smooth brome grass (Bromus inermis) during the second summer. The stand is thrifty even though it had been heavily shaded by wild mustard (Sinapis arvensis) the previous year.*

TABLE 19

WEED POPULATION OF WHEAT FIELDS ON LAND REGULARLY CULTIVATED AND ON LAND PREVIOUSLY SODDED WITH CERTAIN GRASSES

Previous treatment	Days after emergence	Wheat plants (stems) per. sq. m.	Weeds per sq. m.
Continuous cultivation	24	261	53
	41	273	37
	82	246	16
Agropyron cristatum grown for 6 years	24	245	3
	41	389	0
	82	392	0
Agropyron pauciflorum grown for 6 years	24	247	4
	41	377	0
	82	381	0

On the other hand, all the weeds recorded in the field which had been regularly cultivated were either mustard or pigweed. These persisted till maturity and the wheat suffered considerably.

In the sod land the situation was altogether different. The numbers of the weed plants were low, and as a rule they belonged to species generally found on abandoned land or poor pastures, and not to those capable of persistent existence in soils subjected to disturbance under regular cultivation. For this reason, these volunteers should not be regarded as a source of new infestation under a regular cropping system.

These data show conclusively that the grasses, *Agropyron cristatum*, *A. pauciflorum*, and *Bromus inermis*, may be used effectively in a rotation system for control of annual weeds, if the weeds are cut at the time of flowering during the first season after grasses are sown.

Summary

Four aspects of the relationship between roots and soil management were studied. A detailed analysis was made of root systems of three cultivated perennial forage grasses at several stages of development and under different conditions of growth. Quantity and quality of underground parts in the upper 10 centimetres of soil were determined for certain cultivated and prairie grasses, and alfalfa. The effect of the roots and rhizomes of certain grasses upon soil structure was ascertained and the value of certain forage grasses used in rotation with grains for control of common annual weeds was determined. The three cultivated forage grasses were studied in Canada at Saskatoon, Saskatchewan, and the seven prairie grasses, winter wheat, and alfalfa in the United States, near Lincoln, Nebraska. The semi-arid climate supports mixed prairie vegetation at Saskatoon and true prairie at Lincoln.

The entire root systems of crested wheat grass (*Agropyron cristatum*), slender wheat grass (*A. pauciflorum*), and smooth brome grass (*Bromus inermis*), and sods of all species 0.5 sq. m. in area and 10 cm. deep, were exposed by the soil-block washing method. Roots were preserved in four

per cent solution of formaldehyde and later placed in a tank of water for analysis. Length of all main roots and their branches in smaller plants was determined by actual measurement. Number and length of branches of more mature plants were computed from random-sample counts and measurements. The flotation method was used to separate dead root fibre of the cultivated perennial forage grasses from random soil samples taken in fields three years after sods were broken. The amount of vegetable matter was determined both in oven-dry weight and in combustible material.

The number of seminal roots varied within narrow limits in each species of cultivated forage grasses and apparently was governed by a definite genetic factor. The average number per plant on seedlings a month old was 2.4 for crested wheat grass, 1.1 for slender wheat grass, and 2 for smooth brome grass. Large-seeded annual grains developed a greater number of seminal roots than small-seeded perennial forage grasses. Many seminal roots per plant in the latter were a disadvantage. Plants with more than the normal number lacked vigour and soon died. A large number of seminal roots may have exhausted the limited food reserves before sufficient leaves were developed to provide nourishment.

The number of seminal roots produced and the survival of seedlings were related to the depth from which the plants emerged. Most seedlings emerging from a depth greater than 0.5 inch produced an excess of seminal roots and perished within two to four weeks. Likewise, plants germinating on the surface of the soil were weak and died during the first month. Seeds germinating between the soil surface and a depth of 0.5 inch produced vigorous plants with the normal number of seminal roots. A firm seedbed with sufficient soil moisture is essential for normal development of seminal roots of these grasses. Unsatisfactory stands are due primarily to failure to provide a firm seedbed, thus making it difficult to place the seed at the optimum depth. Firm soil, moreover, insures delicate roots against desiccation.

The number of nodal roots, unlike that of seminal roots, was widely variable and depended mostly upon growing conditions. Spaced plants, three months old, which had grown in moist soil, were provided with four times as many nodal roots as similar ones grown in an arid environment. When plants grew under close competition, nodal roots occurred in sufficient numbers to utilize completely available moisture. The ratio of nodal roots of mature spaced plants to those of plants growing in sod was about 95 : 1 for crested wheat grass, 70 : 1 for slender wheat grass and 33 : 1 for smooth brome grass.

Nodal roots penetrated to a depth of 2 to 8 feet and spread laterally to 3 feet or more depending on species, soil type, and moisture. Roots of mature plants with their branches measured a few thousand inches when grown in dense sod and as much as 147 miles per plant for smooth brome grass, 178 miles for slender wheat grass, and 360 miles for crested wheat grass when well spaced.

Nodal roots took over the support of perennial grasses within two months after emergence and were the last organs to stop functioning when a mature individual died. The root system of slender wheat grass developed more rapidly during the first season of growth than those of crested wheat grass and smooth brome grass. The rate of growth of roots of crested wheat grass greatly exceeded that of both other species in the second year, when the increases were 3,100.9, 1,708.8, and 1,418.1 metres per day for crested wheat

grass, slender wheat grass, and smooth brome grass, respectively. The root system of crested wheat grass continued to expand somewhat during the third summer, but that of smooth brome grass remained stationary, and that of slender wheat grass deteriorated.

The total quantity of underground material produced by smooth brome grass after two years of growth was greater than the amount produced by either crested wheat grass or slender wheat grass. At the end of four years, however, underground material from all depths in plots of crested wheat grass weighed 3,790 kg. per acre and exceeded that of smooth brome grass by 1,082 kg. per acre and that of slender wheat grass by 2,378 kg. per acre. In four-year-old sods, more than half the underground material of all species was concentrated in the upper 15 cm. of soil. This was attributed to increase in diameter of roots and crowns and the development of rhizomes.

Dead root fibre of crested wheat grass resisted decay for three years and held the soil from erosion for six years after the sod was broken. Roots of slender wheat grass, on the contrary, failed to hold the soil even one year after the sod was broken. and were largely reduced to dust within three years.

Among the prairie grasses, big bluestem (*Andropogon furcatus*) yielded the greatest quantity of underground material in the upper 10 cm. of soil. This amounted to 2,794.5 kg. per acre. Crested wheat grass among the cultivated forage grasses closely approached this yield with 2,426 kg. per acre. The quantity produced by winter wheat (*Triticum aestivum*) was relatively low, being only 565 kg. per acre, and the quality was poor. Many of its finer root branches died and decomposed before the plants were matured and the main roots underwent the same process soon after the crop was harvested. Consequently, no binding fibre remained in the soil. Bluegrass (*Poa pratensis*) exceeded all other species in total number of roots found in the upper 10 cm. of soil. There were in half a square metre more than 12.5 million main roots and branches, which if placed end to end would have extended 106.7 miles.

Lengths and weights of underground stems were comparatively small. Linear production by western wheat grass (*Agropyron smithii*) was 209.2 m. per square metre and exceeded that of its nearest competitor, smooth brome grass, nearly two and one-half times. Big bluestem and crested wheat grass yielded most by weight with 1,246.5 and 1,243.2 kg. per acre, respectively.

The tensile strength of all classes of roots and of underground stems of each species was determined by means of a tensile strength meter especially constructed for this purpose. Diameters of these structures were accurately measured with a micrometer. Tensile strength of the same root structures with equal diameters varied widely in different species but was closely proportional to diameter within a species. The main roots of crested wheat grass had a mean diameter of 0.4 mm. and a tensile strength of 820 gm. The mean diameter of the main roots of slender wheat grass was greater (0.5 mm.), yet their tensile strength was less than half as great (389 gm.). Rhizomes of little bluestem (*Andropogon scoparius*) and roots of big bluestem exhibited the greatest tensile strength. Roots of bluegrass showed the least actual resistance to pulling forces. Their relative strength, however, was greater than that of other species. Tensile strength of underground structures of winter wheat was very low.

The soil-binding equivalent of a species is the product of the length in centimetres of the roots per cubic centimetre of soil and their tensile strength in grams. High linear production of underground materials in western wheat grass and relatively great resistance of these to pulling gave this species the highest soil-binding equivalent. Winter wheat had the lowest. Species between these in the order of decreasing value were crested wheat grass, big bluestem, needle grass (*Stipa spartea*), smooth brome grass, bluegrass, blue grama grass (*Bouteloua gracilis*), little bluestem, sand dropseed (*Sporobolus cryptandrus*), and slender wheat grass.

Expression of tensile strength and quantity of roots in terms of soil-binding equivalents provides a uniform way to present results and facilitates the comparison of species. These values vary with the age of the plants and the localities in which they grow. Nevertheless, they give certain quantitative concepts as to resistance to erosion.

Considerable difficulty was experienced in expressing differences in structural composition of soil in easily comparable quantitative units. It was observed that structural aggregates of soils taken from different sods disintegrated in water at different rates. This led to the use of water in a special apparatus, called a pedostructometer, for determining the structural condition of soil.

Virgin soils contained from 14 to 20% of structural aggregates from 4 to 0.8 mm. in diameter. In fields under continuous cultivation only 0.5% of these aggregates remained intact. In five years, crested wheat grass restored the topmost layer of soil, which had previously been in continuous grain for more than 20 years, to the condition found in sod of needle grass. Smooth brome grass increased the amount of large soil aggregates nearly four times, but slender wheat grass did not improve soil structure.

At depths exceeding 10 cm., none of the cultivated grasses had an appreciable effect upon soil structure. Soil samples from virgin prairie, however, produced higher percentages of large soil aggregates from depths of 10 to 20 and 30 cm. than in the uppermost layer.

The fact that the percentage of large soil aggregates was high for all species with high soil-binding equivalents seems to indicate that a close relationship exists between the amount and strength of root material of each species and its ability to restore structure of highly pulverized soils. The depth of penetration of roots also seems to play an important part in this respect. In sods of blue grama grass, the roots of which penetrated only to a depth of 45 to 60 cm., large soil aggregates were concentrated in the 0 to 30 cm. depth. Big bluestem, on the other hand, with its strong, deep root system affected the soil structure to a much greater depth. The length of time that land had remained in sod was an important factor. Although root material of crested wheat grass had a higher soil-binding equivalent than that of big bluestem, yet the percentage of large soil aggregates from a five-year-old sod of the former was only three-fourths as great as that of virgin sod of the latter.

The ever increasing population of weed seeds in soil under continuous crops of grain has created a problem so serious that farmers are compelled to employ excessive tillage, which is highly harmful to the structure of soil, to overcome this menace. Most common annual weeds mature and shatter seeds before grain crops are harvested. Many of these seeds remain viable for more than

one year and thus the population of weed seeds becomes increasingly greater. Extensive surface tillage, often used to control these weeds, pulverizes soil and leaves it susceptible to erosion. Consequently, the possibility of reducing the annual weed population by keeping land in sod of crested wheat grass, slender wheat grass, and smooth brome grass was investigated. Experimental plots were established wherein each of the three grasses was grown in competition with each of four common annual weeds, wild oats (*Avena fatua*), common mustard (*Sinapis arvensis*), lamb's quarters (*Chenopodium album*), and penny cress (*Thlaspi arvense*).

All grasses grown in competition with weeds were seriously suppressed. Crested wheat grass showed more resistance to the smothering effect of weeds than smooth brome grass and slender wheat grass. All species of weeds germinated earlier than the grasses and grew more rapidly after germination. They not only occupied the soil with their roots earlier than the grasses but also covered the surface with a rank growth of tops. Common mustard was the most successful competitor with all grasses. It was followed by lamb's quarters, penny cress, and wild oats. All grasses recovered quickly after the rank growth of weeds was cut at the blooming stage.

All grasses took exclusive possession of the experimental plots during the second season. There were readjustments both in the control and the experimental plots. While the grass in the experimental plots grew vigorously as soon as spring opened, that in the control areas remained inactive until the end of May. Stands of grass in many experimental plots were thin and each plant had more moisture and light. This resulted in an increase of stems from tillering and from germination of seed which had remained dormant during the first season. In the control plots where stands had been thick, severe competition took place between the grass plants themselves and, as a result, the number of individuals was drastically reduced.

Beginning with the third season, the stand of slender wheat grass became thin and many volunteer weeds appeared. After four, five, and six years of growth, weeds increased enormously in slender wheat grass, and somewhat in smooth brome grass, but were virtually absent in crested wheat grass. These weeds, however, were not the kind which thrive successfully in habitats annually disturbed by cultivation. Grain sowed in soil, which for six years had grown these perennial grasses, was free of common weeds. This shows conclusively that crested wheat grass, slender wheat grass, and smooth brome grass may be used effectively in a rotation system for control of annual weeds if the weeds are cut at the time of flowering during the first season after the grasses are sown.

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